Design of a Ceramic Matrix Composite Integrally Bladed Turbine Disk

Katherine K. Mims/ED23
205–544–1506
E-mail: katherine.mims@msfc.nasa.gov

This program is in its second year and will enter shortly into Phase II which consists of the actual hardware fabrication and testing. Primary members of the multiple discipline Science and Engineering MSFC/LeRC team are: LeRC: Andy Eckel, Dr. Tom Herbel, Ali Sayir; MSFC: G. Genge, EP32; Dr. Corky Clinton, EH34; Michael Effinger, EH34; Don Harris, ED23; Dr. James Min, ED27; Dr. Roy Sullivan, ED28; Jose Roman, ED64; R. Beshears, EH13; and the author. Subscale tests have been completed to either address simplex turbopump test requirements or to generate gaseous oxygen (gox) or thermal-based data for upcoming programs. The following presents limited results from the subscale tests and analyses that have been performed. Because of ITAR (International Traffic in Arms Regulations) restrictions on export of technologies and the fact that data represents a technology unique to the United States, requests for detailed data may be made through the Technology Transfer Office.

Telecons with DoD and industry participants produced historical design data that enabled the team to quickly identify the key design parameters for composite blisks: shear strength limitation of composites, higher compressive strength of C/SiC composites, the biconic attachment coupling design, and the potential for tailoring blade strength properties through the implementation of ceramic polar weaves.

A preliminary analysis was performed to help determine differences in stress levels experienced with ceramics versus the traditional metallic blisk. In order to be consistent with previous simplex results, the ANSYS simplex turbine blisk model was modified with composite properties for a simple comparative case study and the calculations for maximum stress and blade hub values were presented to the team. While stress values were lower for the ceramic case, only centrifugal loading was considered at this time for this particular phase of the design. Examination also was made of three attachment designs, based on earlier work performed by Garrett Aircraft in the early 1980's. In the future, a blisk model with a bionic attachment definition will be used for structural assessment. The blisk geometry will be finalized when subscale torque test results are available for incorporation into the hub attachment design. Additional work was performed to provide recommendations for high cycle fatigue and low cycle fatigue test parameters.

With key composite integrally bladed disk (CBLISK) design parameters identified from the industry-government telecons, and guidance in use of the design of experiments approach, a test matrix for the torque testing was generated for optimizing the blisk hub attachment design. Due to funding limitations, however, the test matrix will be reduced to reflect evaluation of two designs rather than three.

Several subscale tests were performed to resolve materials performance questions for blisk concepts in general; a few tests address simplex-specific turbopump test requirements for turbines operating in a gox environment.

Damping tests were performed on eight beam samples, two of which were provided by the CDDF (Center Director's Discretionary Funds) damping study entitled "Measurement of Damping of Advanced Composite Materials for Turbomachinery Applications." The tested materials included two samples each of:

- C/SiC Quasi-Isotropic
- C/SiC (0/90)
- C/SiC (0/90) 15-degree offset
- SiC/Alumina

Figure 52 shows the results of the testing compared with an Inconel 718 beam sample. The results indicate a significant increase in damping over the metal sample. The C/SiC (0/90) 15-degree offset sample was dropped before testing which probably caused more matrix cracking, which in turn allowed more slip and produced more damping for all modes tested. Additionally, the two disks procured from Oak Ridge National Laboratory for damping tests in the CDDF task were provided to the CBLISK team for torque requirements testing.

Three thermal testing tasks were conducted at NASA/LeRC on the C/SiC composites. These were thermal shock, stressed

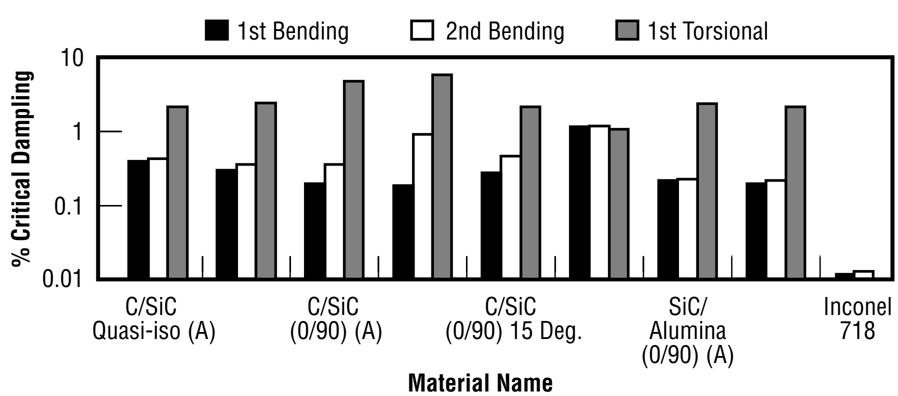

FIGURE 52.—CDDF/CBLISK beam samples damping results (FY96).

oxidation and thermogravimetric (TGA) testing. Due to funding limitations, it was decided by the team to divide the testing into two phases; Phase II is planned for FY97.

The first set of stressed oxidation testing was completed and analysis of the results was reported. TGA testing was also partially completed and results are available. TGA testing was performed on both fiber architectures and at three temperatures. This testing is meant to assess how rapidly the materials oxidize (without stress) in a flowing oxidizing gas at elevated temperatures. Weight loss data is recorded in real time as the sample is suspended unstressed in a laboratory furnace. Each test runs for a maximum of 24 hr. So far, the TGA data are consistent with results from the stressed oxidation testing. These data and plots are available upon request.

Results for the particle impact test of coated C/SiC targets indicated that the samples do not burn at temperatures up to 700 °F. In most impacts, the material appeared fragmented and de-layered rather than burned. More tests will be run to generate additional data. Remaining samples will be reserved until the injector is redesigned (beginning in 1997) to handle 1,000 °F. Particle impact test data from LeRC exist on SiC/SiC samples; it is reported that the SiC/SiC samples fared well.

Promoted combustion and frictional ignition tests were performed to satisfy pump test requirements. Materials characterization (fatigue, tensile, shear, modulus, specific heat, etc.) tests were also conducted using C/SiC specimens. These properties will be used in the structural assessment.

Many components can be subjected to a spectrum of loading frequencies ranging from a few hertz to several thousand hertz. During its design sessions, the team established the influence of high-cyclic loading frequency on the tensile fatigue life of a woven-carbon-fiber/SiC-matrix composite turbine blisk. Published literature identified frequencies affecting the properties of the ceramic composites. Recent fatigue studies, conducted at University of Michigan, have shown that the tension-tension fatigue life of fiber-reinforced ceramics decreases as the fatigue loading frequency is increased. A limited number of samples were used in load-unload tests for predetermined stress levels and frequency of cycling parameters identified for the high-cycle fatigue testing. Fatigue data on tensile specimens were generated. An attempt was made to begin to characterize the composites under various loading conditions while operating at 10 and 50 Hz. See figure 53 for a plot of the data. Test failures were discovered at a high number of cycles (i.e, 1×10^7) for high loads. Previous testing for other materials (i.e., metals) would have assumed run out at a lower number of cycles (i.e., 1×10^6). More samples are required to better define this finding. Due to limitations of the test machine, high load and high frequencies could not be obtained. While the low number of samples prohibit a statistical characterization, it does suggest a general trend of the current C/SiC material specimens for the specified test conditions. It is important to note that the frequency dependency of composites is a design factor that will impact structural response and should be characterized as close to operating frequency as practical for planned applications.

In addition to the wrap-up of the FY96 subscale tests, preliminary analysis and developing requirements for the critical design parameters, the team completed a benchmark evaluation of Oak Ridge National Lab (ORNL) rapid densification process through acquisition and nondestructive evaluation (NDE) of polar woven disks. Improved MSFC NDE in-process inspection procedures were established for composites. The actual CMC test blisks will, however, be produced by DuPont through the traditional densification

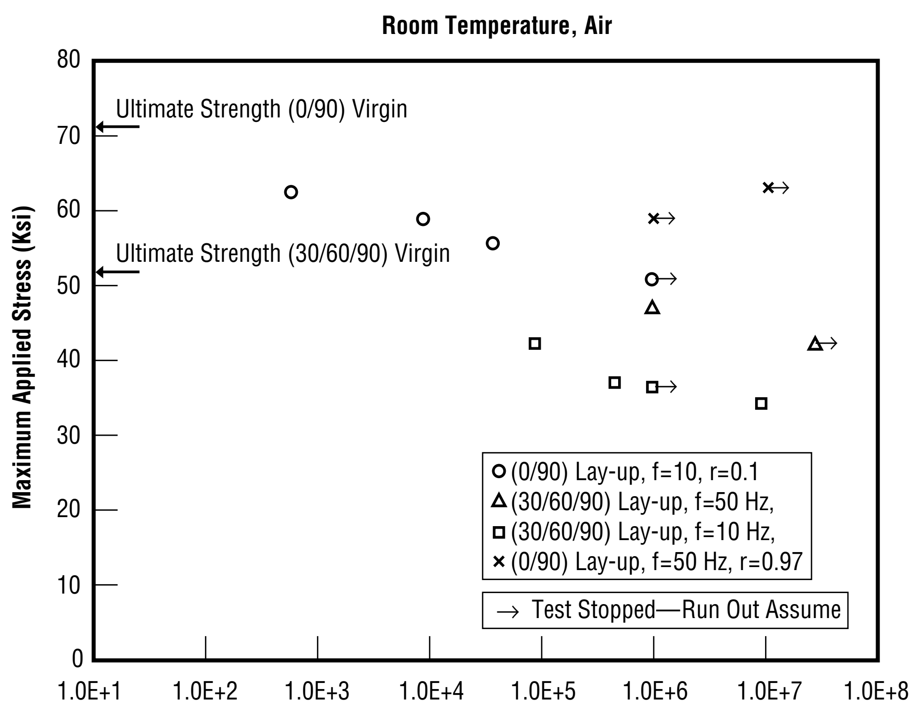

FIGURE 53.—Fatigue of C/SiC ceramic matrix composite.

process. One disk from each type (quasi-isotropic and polar weave) will be used in the turbopump tests.

Fewer parts count and the lighter weight parts will result in reduced operational costs. Acquisition of CBLISK technology is desired to realize cost savings from two areas. Use of a single-piece turbine construction (integrally bladed) damped lightweight composite materials will reduce weight and cost of labor intensive operations of assembly and disassembly, as well as for inspection of complex blades/damper systems. In addition, use of composites is expected to impart needed internal damping to the configuration to address the vibratory stresses encountered due to unsteady flow loads through the bladed turbine regions. However, the structural response of these single-piece structures (blisks) to high-vibration environments must be considered. This task will aid in characterizing the extent to which composites can damp these vibrations and will help benchmark the ceramic blisk technology for application in high-temperature environments. In addition, unique gox-rich environments data will be generated which will broaden the application of composites.

During the progress of this year, this program has produced data which will enable the ceramic matrix composite integrally turbine to be tested in the Simplex turbopump environment. Biconic attachment design parameters were identified and a design of experiments for determining torque test friction factors was formulated. In addition, a limited set of unique frequency/fatigue data base reveals the dependency of composites under high frequency cyclic loading to stress levels which will aid in the characterization of future composites applications.

[1]Turbine Rotor Development Program, DuPont Lanxide, October 1994. Sponsor: Aero Propulsion and Power Laboratory, Wright Research and Development Center, Wright Patterson Air Force Base, Ohio.

[2]Halbig, M.: "Stressed Oxidation Testing." Technical Report, NASA Lewis Research Center, February, 1996.

[3]Clinton, R.G.: "Selection and Characterization of Ceramic Matrix Composite Materials for Rocket Engine Integrally Bladed Turbine Disks (Blisks)." Presented at the annual conference of Advanced Composites sponsored by American Ceramics Society, January 1996.

Sponsor: Office of Space Access and Technology

University/Industry Involvement: DuPont Lanxide; Southern Research Institute, Foster Miller

Biographical Sketch: Katherine Mims is a senior structural dynamics analyst at the MSFC Structures and Dynamics Laboratory, Structural Analysis Division, Structures and Loads Branch. She is a mechanical engineering graduate of Auburn University and has been interested in blisk dynamics since she became affiliated with the Government through DoD/MICOM, Redstone Arsenal in 1983 and then, at MSFC, NASA in 1985.